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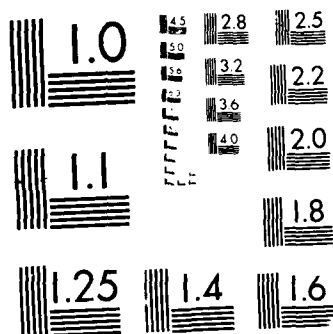
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Final Technical Report  
BASIN ACOUSTICS IN THE ARCTIC OCEAN  
Contract No. N00014-77-C-0266  
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Enclosed:

"Long, Range, Low Frequency Acoustic Backscattering: A Survey", by  
A.B. Baggeroer and I. Dyer, MIT

"The Science Program of FRAM Experiments in the Eastern Arctic Ocean",  
by A.B. Baggeroer, MIT, F.R. DiNapoli, NUSC, T.O. Manley, Columbia  
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"Acoustic Array Sensor Tracking System", by K. von der Heydt, G.L. Duck-  
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"Environmental Correlates of Pack Ice Noise", by N.C. Makris and I. Dyer,  
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The Science Program of the FRAM Experiments in the  
Eastern Arctic Ocean

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#### Abstract

The experiments of the FRAM program were located in the Pole and Nansen Abyssal Plains of the eastern Arctic Ocean. During the four year span (1979-1982) of the series primarily sponsored by ONR, extensive experiments in physical oceanography, ocean acoustics and marine geophysics were conducted from a series of drifting, manned ice stations by scientists from the U.S., Canada and Norway. The physical oceanography measurements included C/STD profiles and transects, water sampling and current meter profiles. The acoustics of long range, low frequency propagation with both explosive and coherent sources, transoceanic basin backscattering, ambient noise and its ice generation mechanisms were studied. In the geophysical experiments seismic reflection and refraction, bathymetric soundings, heat flow, gravity and coring were done.

Conducting these experiments in the Arctic required some creative approaches and opportunities not only as a result of the cold but more importantly the near continuous ice cover. The geophysical and acoustics experiments centered upon two dimensional, multichannel hydrophone arrays and ocean bottom seismometers. The physical oceanography program covered extensive areas by helicopter using portable CTD profilers. The data set gathered over the four years is the most extensive available from this part of the Arctic Ocean. This paper gives an overview of the technology used for the FRAM science program and representative results of some of the investigations. The logistics of the staging and conducting the experiments are covered in a companion paper [Hielscher, 1985].

#### Introduction

Beginning in 1979 the Arctic Program of the Office of Naval Research directed its research activities north of the Fram Straits in the eastern Arctic. The FRAM experiments were a series of ice camps drifting on the pack ice and were conducted in the spring of each year from 1979 to 1982. The drift tracks of the four FRAM ice camps are indicated in Fig. 1. FRAM I [Hunkins, et al. 1979] and FRAM III [Manley et al., 1982] emphasized physical oceanography and marine geophysics while FRAM II [Baggeroer and Dyer, 1980] and FRAM IV focused

upon underwater acoustics and marine geophysics [Kristoffersen, 1982].

This region of the Arctic Ocean is of particular importance for several reasons. From the physical oceanography perspective the Fram Strait which lies between Greenland and Spitzbergen is by far the most important of the passages that connect the Arctic with the other oceans. The Fram Strait is where the major amount of heat, salt and mass are exchanged by way of the cooler and fresher outflowing polar waters and the warmer and more saline inflowing Atlantic waters. In order to better understand the role of the Arctic in the determination and modification of climates, both locally and globally, important processes which control the transfer of heat, mass and salt within the context of the very complex interactions of air, sea and ice need to be defined quantitatively [Barry, 1983]. During the FRAM program the major concerns of the physical oceanography experiments were i) a more quantitative examination of the vertical heat exchange between the atmosphere and ocean through the ice cover; ii) the spatial and temporal variability of the upper layer (< 500 m) oceanic structure, horizontally and vertically, which resides beneath the permanent ice cover [Manley, et al., 1982].

As a result of the unique oceanography acoustic propagation in the Arctic differs from that in more temperate waters in many ways. The nearly isothermal water leads to an upward refracting sound speed profile with the minimum at or very near the surface. Transmitters and receivers are usually within the axis of the SOFAR channel which leads to dispersive propagation [Kutschale, 1966]. The ice cover also insulates the water from the mixing effects of the atmosphere; consequently, the Doppler spreading of signals is exceptionally low [Mikhalevsky, 1981]. The ice cover and models for it introduce significant losses above 50 Hz due to mechanisms which are still poorly understood [DiNapoli, 1985]. The ambient noise is very different in the Arctic. The cacophony of sound from the ice cover is filled with signals that have no equivalents in warmer waters [Dyer, 1982]. Finally, the ice cover provides a unique platform to deploy two dimensional arrays for studying the

directional properties of ambient noise and reverberation and for multichannel seismics.

The vast majority of low frequency Arctic propagation experiments reported in the open literature before 1980 were conducted in the western Arctic using explosive sources, c.f. [Kutschale, 1966]. The primary result of these experiments, which lasted for a number of years and over many locations in the deep pack ice, was the broadband propagation loss. During these investigations the qualitative evidence of the stability of Arctic propagation became evident by the remarkable similarity in the signals detonated at the same location but at different times. Ambient noise was also studied extensively in these experiments [Greene and Buck, 1964].

The major objectives of the FRAM acoustics experiments were i) to understand low frequency acoustic propagation including the energy partitioning among the water, ice and bottom interaction; ii) to determine the stability and coherence of narrowband signals; iii) to measure the ambient noise and relate its source to the ice mechanisms and iv) to conduct basin reverberation studies using two dimensional arrays.

The Pole and Nansen Abyssal Plains of the eastern Arctic or bisected by the Nansen, or Arctic Mid-Ocean Ridge. This ridge is a spreading center with a spreading rate of 1 cm/yr, one of the lowest for the world's oceans [Jackson, 1982]. The drift tracks for the FRAM ice stations were over the abyssal plains, the flanks of the adjacent Morris Jessup Rise and the Yermak Plateau, and the mid oceanic ridge. While the magnetic anomalies provide a reasonably clear picture of the overall tectonic evolution of these regions, no direct deep seismic measurements were available beyond the bathymetric soundings and shallow profiles of the drifting station, Arlis II [Ostenso, 1977].

An extensive program of seismic refraction and reflection was conducted during the FRAM series to determine the age and formation processes for these regions of the Arctic. They were the first and remain the only direct measurements of the oceanic basement structure in this part of the Arctic. The specific objectives of the marine geophysical experiments were i) determine the crustal velocity structure of the crust as the ice stations drifted; ii) date the age of the oceanic basement using the Parsons-Sclater age versus depth to unloaded basement formula and compare this to that predicted by the magnetic anomalies; iii) determine the seismic structure of the sediment column [Kristofferson, et al. 1981; Duckworth, et al., 1982; Jackson, et al., 1982; Duckworth, et al., 1985].

This paper gives an overview of the technology used for the FRAM program and a representation of some of the scientific results. The papers in the bibliography provide much more detail on the individual scientific results, while the logistics of staging and executing the experiment are described in a companion paper [Hielscher, 1985].

#### Physical Oceanography

The constraints imposed by the near continuous ice cover and its surface roughness restrict the use of fixed wing aircraft for many scientific experiments where location control is needed. For example, tracking highly variable structures such

as oscillating fronts and eddies and local dynamics is very difficult without spatial coverage since one cannot separate space and time effects at a single site. While fixed wing craft have the necessary range and payload capacity, often few flows are suitable for runways. Damage to the landing gear on unproven runways can and does occur even to the point of the loss of an aircraft during the FRAM III experiment when it sank through thin ice.

During the FRAM series a Bell 204 helicopter was used extensively for many of the science programs, especially for the C/STD surveys. With careful attention to size, weight and range restrictions, the helicopter proved to be an invaluable asset to the scientific experiments (and the camp logistics as well). Oceanographers at Lamont designed a helicopter based C/STD system around the first commercially available, light weight, internally recording unit, model 202 C/STD marketed by Ocean Data Equipment [Manley, et al. 1980]. The C/STD system is illustrated in Fig. 2. It consisted of the unit itself plus a winch, electric hand drill, a 2 kw, 110 VAC generator and a chainsaw. The generator powered the hand drill which in turn ran the winch. The winch was a small and light weight unit equipped with 500 m of 5/32 inch Kevlar cable and was mounted on an aluminum cantilever/tripod which also served as a guide for the cable through the ice. The chainsaw was used to cut through thin ice when a open lead was not available. Total weight of the system was approximately 200 pounds. One person could operate the system although it was convenient to have two to reduce the time at each station.

Navigation for the CTD surveys was done using the OMEGA/VLF system aboard the helicopter and was accurate to  $\pm 500$  m at the latitudes of the camps. Normal distances of the surveys extended 100 km from the main camps.

The values of pressure, temperature and conductivity were recorded at a sampling rate of 5 Hz with a digital resolution of 12 bits over a selected range of each sensor on a cassette tape. Each cassette was capable of holding 1.6 Mbits of data, or 1.5 hours of operation. Although each station took but .5 hours, just one cassette was used per station in order to verify a successful cast and to eliminate the possibility of running out of tape in the midst of a cast. The C/STD sonde used a rechargeable battery pack with a lifetime of 5 hours at the low temperature of the water column. At typical lowering and raising rates this permitted five to eight stations normally to be taken within the fuel payload limitations of the helicopter.

The raw digital data were converted in the field to plots of pressure, temperature and salinity which were mapped into plan views. Depending upon the features observed the sampling pattern for the next survey was determined. This "real time" monitoring enable scientists in the field to track the interesting feature and optimize the available helicopter time instead of relying upon blanket sampling over the entire region. Using this mode of operation a total of 204 helicopter C/STD stations were obtained during FRAM I, II and III. An additional 214 C/STD stations were obtained from deployments at the camps. The positions of these station are indicated in Fig. 1. They are the

largest set of nearly synoptic C/STD data in the eastern Arctic. Further advances in helicopter C/STD surveys were obtained using the newer 302A Ocean Data Equipment model which is lighter, smaller and more sophisticated electronically and can operate for up to 12 hours. This has permitted surveys using smaller helicopters such as the Bell 206B Jet Ranger [Manley and Perti, 1984].

Long term synoptic information can be gathered very efficiently with remote drifting buoys linked via satellite communications. In the Arctic this was demonstrated during the Arctic Ocean Buoy Program where large scale ice motion and atmospheric temperature and pressure were mapped [Thorndike and Colony, 1980]. Two buoys for monitoring the upper ocean processes in the Arctic were developed by the Polar Research Laboratory (PRL) and tested during the FRAM program [Manley, et al., 1982]. The first was equipped with a 200 m thermistor chain with 20 m spacing. The second had three pairs of temperature-conductivity sensors at depths of 15 m, 30 m and 50 m. Both buoys operated using the ARGUS satellite data reporting system. Both functioned well during the FRAM III program, and the thermistor chain buoy was allowed to free drift with the East Greenland current after the experiment. As an example, Fig. 3 indicates the general thermal structure of the upper 200 m of the water column obtained with the buoy.

#### Ocean Acoustics

The experiments in ocean acoustics used large multichannel hydrophone arrays deployed through the ice. In addition, several small satellite camps were deployed which broadcast coherent and explosive signals to the arrays at the main camp. Fig. 4 indicates the drift track of the FRAM II and FRAM IV camps and their associated satellite camps. FRAM II had two dimensional horizontal array roughly .8 m x 1.0 km. Its layout changed significantly during the experiment because of an ice breakup. FRAM IV had both a 1.6 km x 1.2 km horizontal array and a 1 km vertical array. The interelement spacing on all arrays varied in order to achieve both a broad band capability as well as wide apertures for high angular resolution. Fig. 5 illustrates the FRAM IV arrays as an example. The data from the horizontal arrays were digitally recorded using a Hewlett-Packard 1000 minicomputer and gain ranging amplifiers with a 120 dB dynamic range. Twenty four channels of data over an 1 - 80 Hz band were recorded at a 250 Hz sampling rate [Prada, et al. 1981]. Over 700 digital tapes were recorded in each experiment. During FRAM IV thirty channels of the vertical array data were recorded analog tape over a band up to 1250 Hz. With a reasonable amount of care to minimize thermal stress and static electricity both the digital and analog recording systems were very reliable.

During FRAM II a Hydroacoustics HLF-3A program-mable source at Camp 1 343 km and an NRL Mark 6 tonal source at Camp 2 approximately 1000 km away transmitted signals to the receiving array. Both transmission paths were over deep abyssal plains. During FRAM IV just the HLF-3A source was used from Camp Tristen over a 238 km path which traversed the complex bathymetry of the mid ocean ridge. Both of these sources produce very high signal levels, e.g. 76 dB re 1  $\mu$ Pa @ 20 Hz for the HLF-3A, over a

broadband capability from 5 to 200 Hz. These sources were supplemented by explosive shots as sources using weights from .9 kg SUS charges to 50 kg TNT demolition charges at depths of 19, 93 and 243 m.

The results of the coherent source measurements are reported by Mikalevsky, 1981 and Di Napoli, 1984 and are only summarized here. The inter-element coherence was measured as a function of sensor separation. It was found to be very high at all frequencies from 17 to 97 Hz with the lowest obtained at 97 Hz at FRAM IV along a leg in endfire direction to the source. This is illustrated in Fig. 6. Even at the maximum separation of 1300 m, or approximately 85 wavelengths, the narrowband coherence remains above .75. Extrapolating the fit on Fig. 6 suggests that the "1/e coherence length" is approximately 4 km at 97 Hz.

The high temporal stability of acoustic signals transmitted in the Arctic Ocean was demonstrated during the FRAM experiments. The "worst case", i.e. the highest Doppler spreading, is indicated in Fig. 7 by the amplitude of the demodulated complex envelope for a 97 Hz tone over a period of 1 hour. There is a 10 minute fade of approximately 10 dB which is probably caused by some instability in the ocean. However, even with this fade the Doppler spread is only 4 mHz, or .0004 % of the carrier.

The vertical array deployed during FRAM IV provided a unique data set on the vertical structure of acoustic signals. Because of the upward refracting profile the sound speed minimum is at or near the surface and individual modes propagation at low frequencies are readily identified [Polcari, 1983; Yang and Giellis, 1984].

The explosive signals transmitted between the canmps have the modal dispersive characteristics observed in the western Arctic [Kutschale, 1966] plus bottom interacting components. The modal components were very similar for both FRAM II and FRAM IV; however, the bottom interacting signals observed during FRAM II persisted for more than 60 seconds while those in FRAM IV were very weak and virtually nonexistent. This was primarily due to the differences in the bathymetry of the transmission path; in FRAM II it was over the Pole Abyssal Plain, whereas in FRAM IV it crossed the Arctic Mid-Ocean Ridge which scattered the bottom interacting energy and stripped off the forward scattered components. The results are reported in Baggeroer and Duckworth, 1982 and Duckworth, 1983.

Ambient noise in the Arctic is strongly coupled to the ice cover [Dyer, 1982]. In addition, micro-earthquake signals were observed because of the proximity of the camps to the Arctic Mid-Ocean Ridge, an active spreading center [Keenan and Dyer, 1983]. The ice responds to wind, current and thermal forces and develops internal stresses to produce ambient noise which is unique in the worlds oceans. Not only are the ambient noise spectra different with characteristic peaks associated with the various stress mechanisms and fracture sizes, but also the time signatures contain distinct events suggesting a Poisson as well the more customary Gaussian process component. Fig. 8 is a composite spectra of many measurements made at FRAM II and is indicative of broadband characteristics of deep Arctic ambient noise.

The depth dependence of ambient noise was also measured using the vertical array during FRAM IV [Yang and Giellis, 1984]. Spectral levels as a function of depth and modal decompositions were determined using several of the high resolution algorithms recently published in the signal processing literature.

Long range, low frequency backscattering (reverberation) from explosive signals has been shown to be highly correlated with bathymetric features, c.f. [Dyer, et al. 1982; Baggeroer and Dyer, 1985]. A sequence of backscattering experiments were done during FRAM II and IV which exploited the two dimensional resolution capabilities of the hydrophone arrays. Transoceanic echoes from topographic features surrounding the Beaufort Sea more than 2700 km away were detected. At closer ranges several locations generated unusually high backscattering levels during both experiments which has called into question either our theories on backscattering or the charted bathymetry of these locations.

#### Marine Geophysics

The overall structure of the eastern Arctic fits well within the existing theories of seafloor spreading about the Arctic Mid-Ocean Ridge. While basin ages can be tentatively identified with magnetic lineations, there were no direct measurements of crustal structure in this region until the FRAM series. Moreover, the tectonic evolution of the adjacent Morris Jessup Rise and Yermak Plateau was uncertain. Extensive seismic refraction programs were carried out during all the FRAM experiments [Kristoffersen, et al. 1980; Duckworth, et al. 1982; Jackson, et al., 1982; Jackson, et al., 1984; Duckworth, et al. 1985]. They are compiled in Fig. 9. In addition, single channel seismic reflection was done on FRAM I and III and a multi-channel program was done on FRAM IV [Jackson, 1982; Kristoffersen, 1982].

The single channel reflection programs consisted of using a small airgun (40 cu in) detonated approximately every 10 - 15 minutes. As the ice drifted this produced a random line with general direction along the mean drift of the ice field. When the sediment cover was thin, these profiles penetrated to the basement. The multichannel system employed a line of approximately 20 standard omnidirectional sonobuoys spaced every 100 m and transmitting back to a DFS-V seismic recorder [Kristoffersen, 1982]. A 40 cu in and/or 120 cu in air gun depending upon which was operational was used for a source. The seismic line produced had several meanders to it, but it could be roughly stacked along the mean drift direction. It resolved some of the sediment strata and revealed a rough basement topography beneath.

The seismic refraction experiments utilized the two dimensional arrays, the sonobuoy array as well as single hydrophones and ocean bottom seismometers. The constraints imposed by the ice cover demand a different approach and provides an unique opportunity compared to experiments in open water. The ice cover severely limits ones mobility, helicopters are virtually the only means to get to shooting sites on a refraction line. Moreover, during the early spring when all the FRAM series took place, the ice was packed densely, so the

ability to deploy shots through the ice and thus the coverage density was sometimes restricted as well. This sparse shooting coverage was compensated by the redundancy obtainable with the multichannel arrays and the ocean bottom seismometers.

There were essentially two approaches to the seismic refraction data used during the FRAM series. In FRAM I and III only single sensors, the ocean bottom seismometer and a surface hydrophone were available. The inversion approaches consisted of fitting synthetics to the first arrivals and some of the readily identifiable multiples.

During FRAM II and IV the approach to the seismic refraction exploited the multichannel arrays and is described in [Duckworth, et al, 1982] and is only summarized here. First, range for each shot was computed using a shot instant recorder synchronized to the time base of the data acquisition computer and the onset of the very energetic water wave signal. (This was corrected for the sound velocity profile and convergence zone effects.) Next, the azimuth was determined by beamforming on the water wave signal. The multichannel data for each shot were then processed to generate a slowness-travel time spectra such as the one indicated in Fig.10. These spectra are similar to velocity spectra used in seismic reflection analysis except that it is done over several frequency bands and uses a high resolution algorithm. It indicates the distribution of observed energy within a window as a function of travel time and apparent horizontal slowness across the array. The "significant" events in these spectra as well as their multiplicity are selected. These events and all the ones from the other range offsets are compiled by mapping them into the tau-p (intercept time - offset) plane. Finally, the events in this plane are migrated by an inversion algorithm to an estimate of the crustal sound speed versus depth.

The crustal measurements of the FRAM series were consistent with the basement ages predicted using magnetic anomalies and the Parsons-Sclater theory for the basement depths. In addition, many of the issues regarding the adjacent margins of the Morris Jessup Rise and the Yermak Plateau were resolved.

#### Conclusions

The FRAM series compiled the most extensive data set to date on physical oceanography, ocean acoustics and marine geophysics of the eastern Arctic Ocean. The data has been used not only by scientists on the ice stations, but also by numerous investigators in their research about the Arctic. The data are still being used with the renewed interest in the Arctic.

#### Acknowledgement

The FRAM series was primarily sponsored by the Arctic Program Office of ONR. Particular acknowledgement goes to Dr. G. L. Johnson for his guidance throughout the FRAM program. The authors are sure that they speak for all the participating scientists in acknowledging the logistical support from the Polar Science Center of the Univ. of Washington, the crews of Bradley Air and the U.S. Air Force and the personnel at Thule Air Base and Station Nord.

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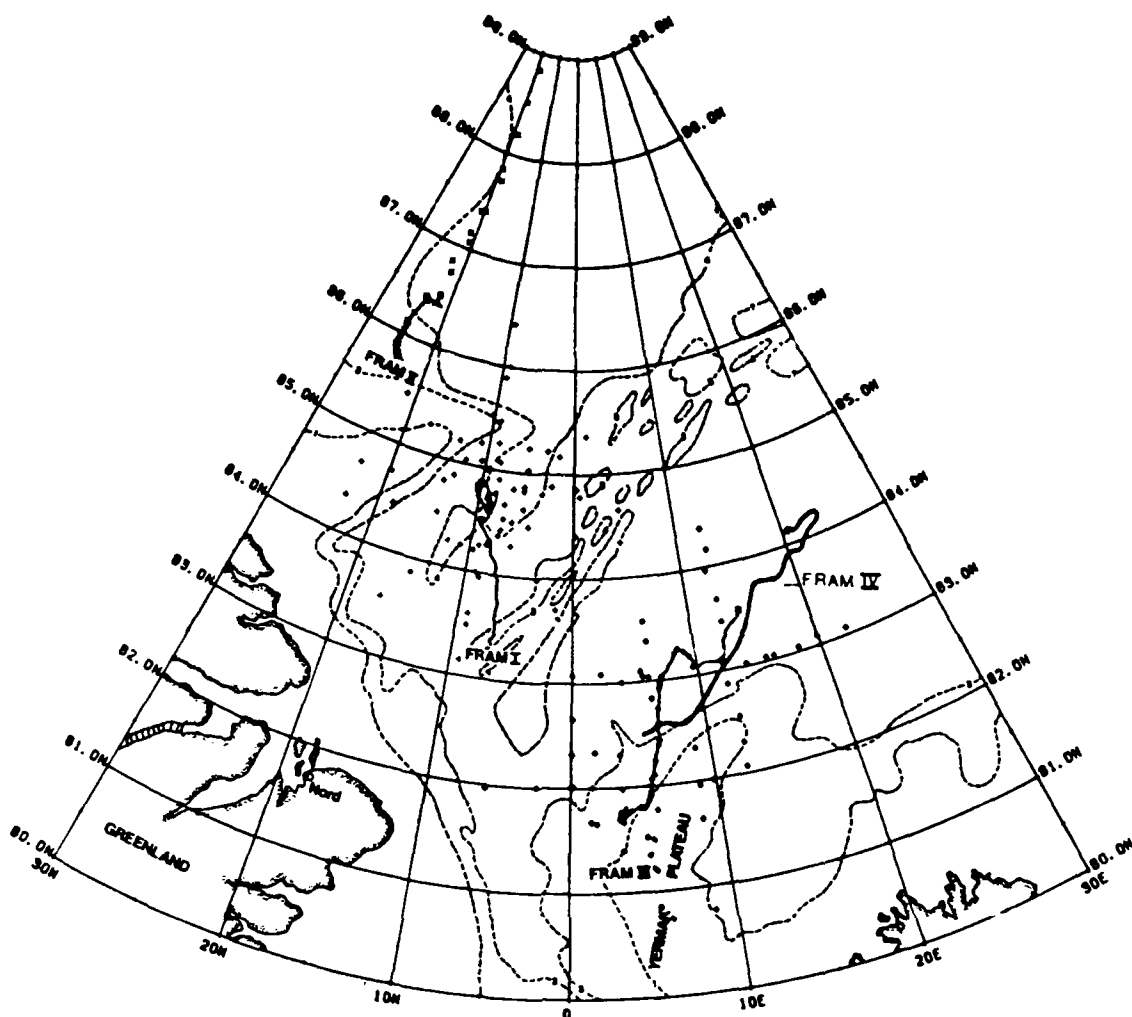
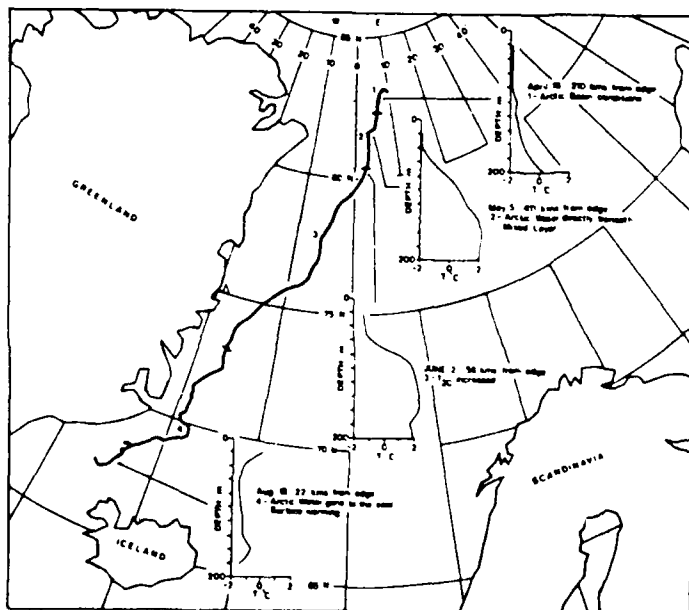


Fig. 1 Drift tracks of the FRAM ice stations 1979 - 1982. The  $\pm$  indicate C/STD station location taken with the Lamont-Doherty helicopter based system



Fig. 2 The Lamont-Doherty helicopter C/STD unit (above) at a station. Generator is at bottom, left; tripod support is in center; C/STD is ready for deployment through hole cut by chainsaw.  
Fig. 3 Profiles from satellite linked thermistor chain after FRAM III (right)



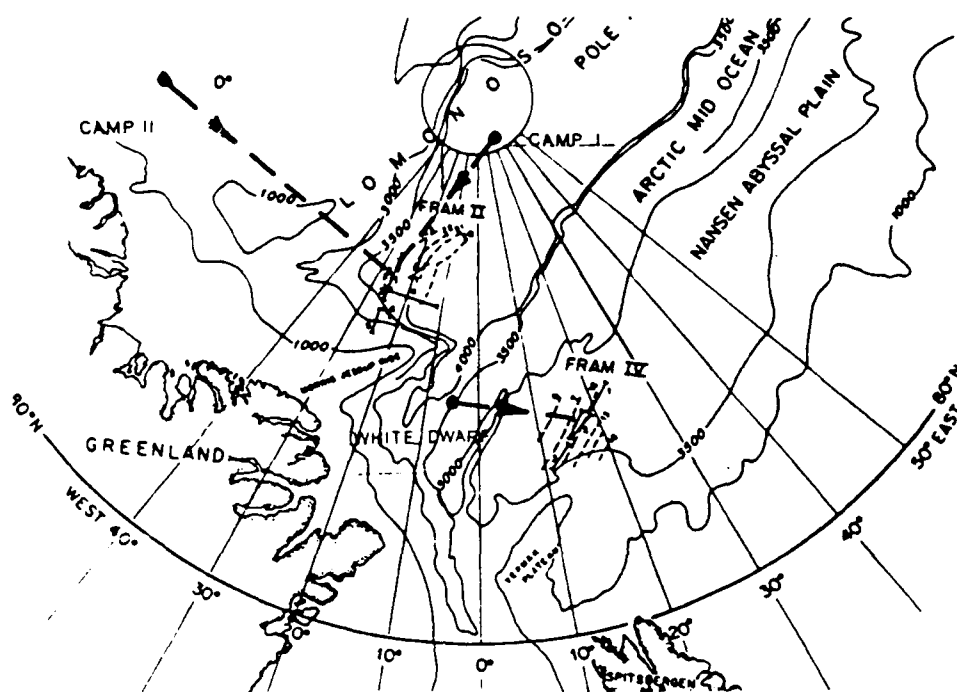


Fig. 4 Paths for the acoustic transmission experiments during FRAM II and FRAM IV. Camps I and II transmitted signals to FRAM II; White Dwarf transmitted to FRAM IV

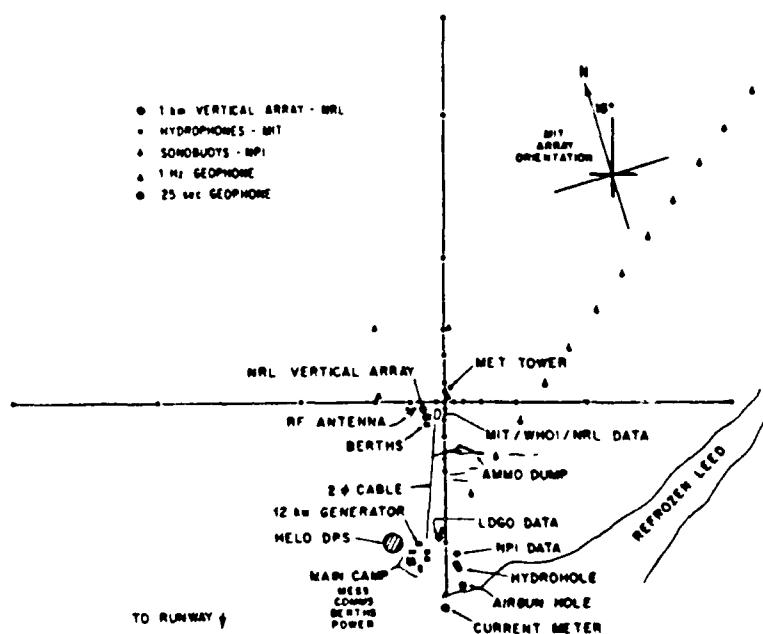


Fig. 5 Layout of the FRAM IV ice camp indicating the multichannel arrays. The two dimensional, crossed array and the vertical were hardwired to recorders; the sonobuoy array was by rf link

Fig. 6 Coherence vs. sensor separation for the FRAM IV experiment. 238 km transmission path at 97 Hz

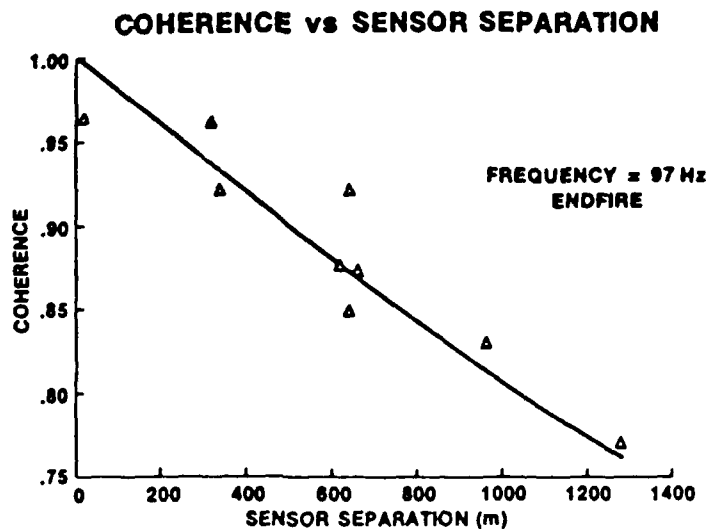


Fig. 7 Complex demodulated envelope for the FRAM IV experiment. Note fade in the 20 - 30 min interval. Doppler spread in approximately .0004 Hz.

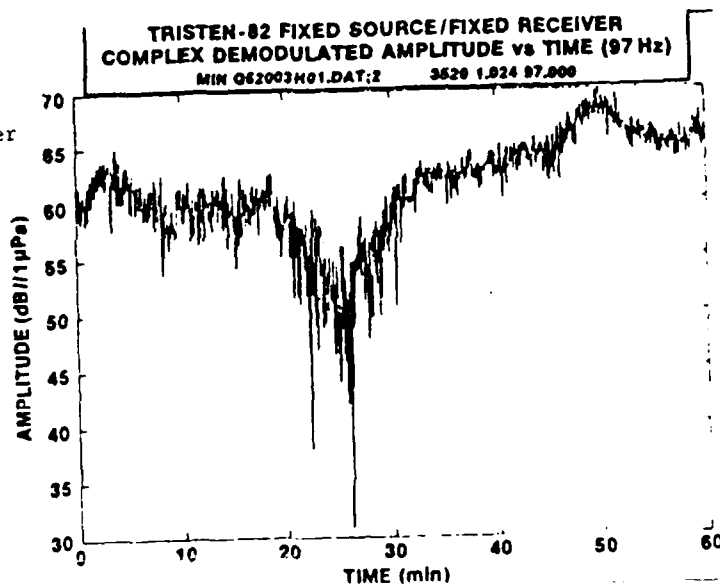
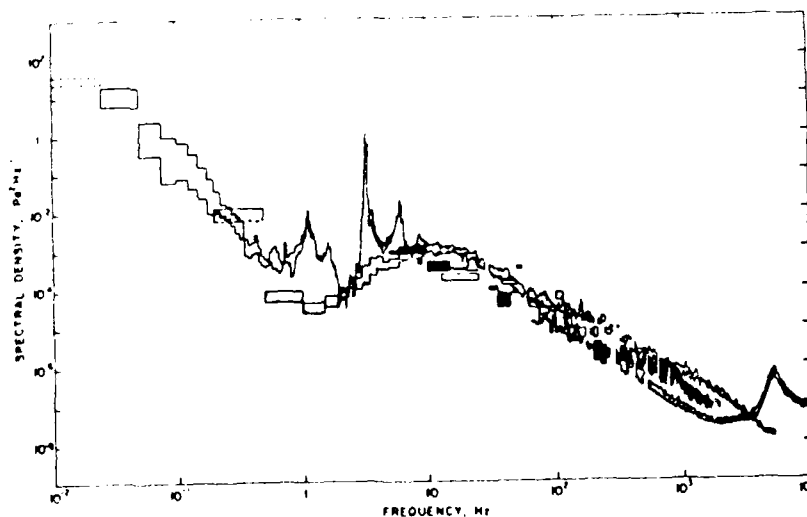


Fig. 8. Composite ambient noise spectra from the FRAM IV experiment. High peaks at low frequency are strum induced.



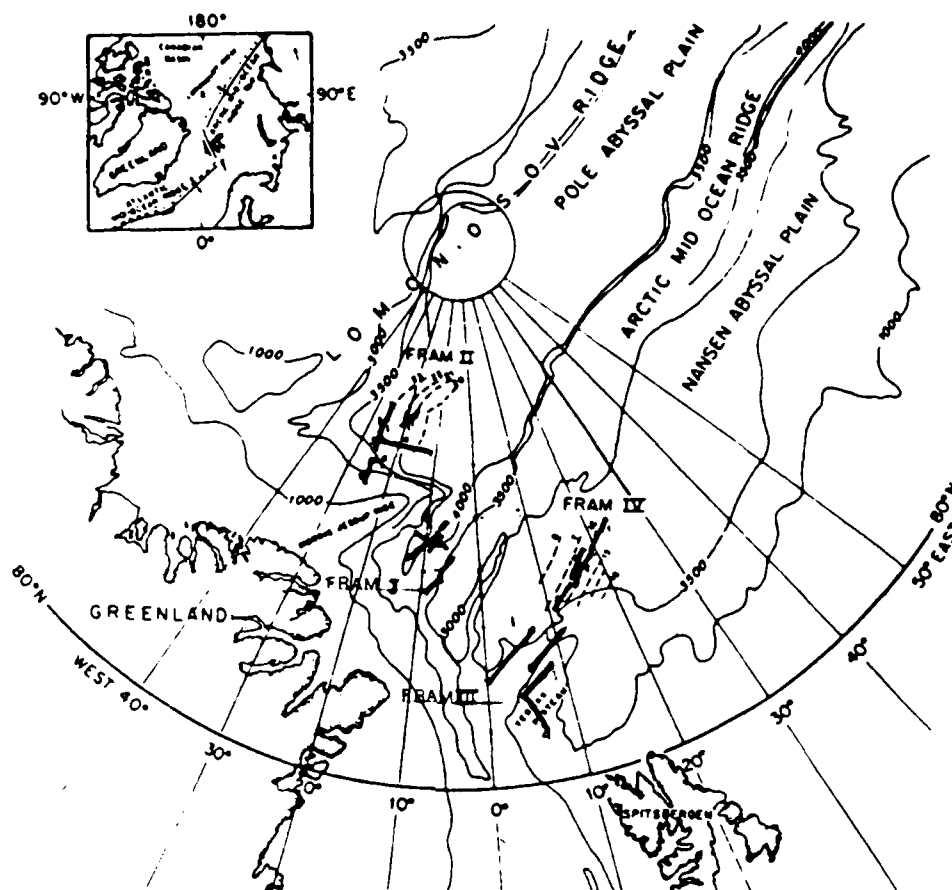


Fig. 9 Locations of the refraction lines shot during the FRAM program. All the lines were unreversed, but shot in opposite directions when possible. The lighter lines near FRAM II and FRAM IV are the magnetic anomalies.

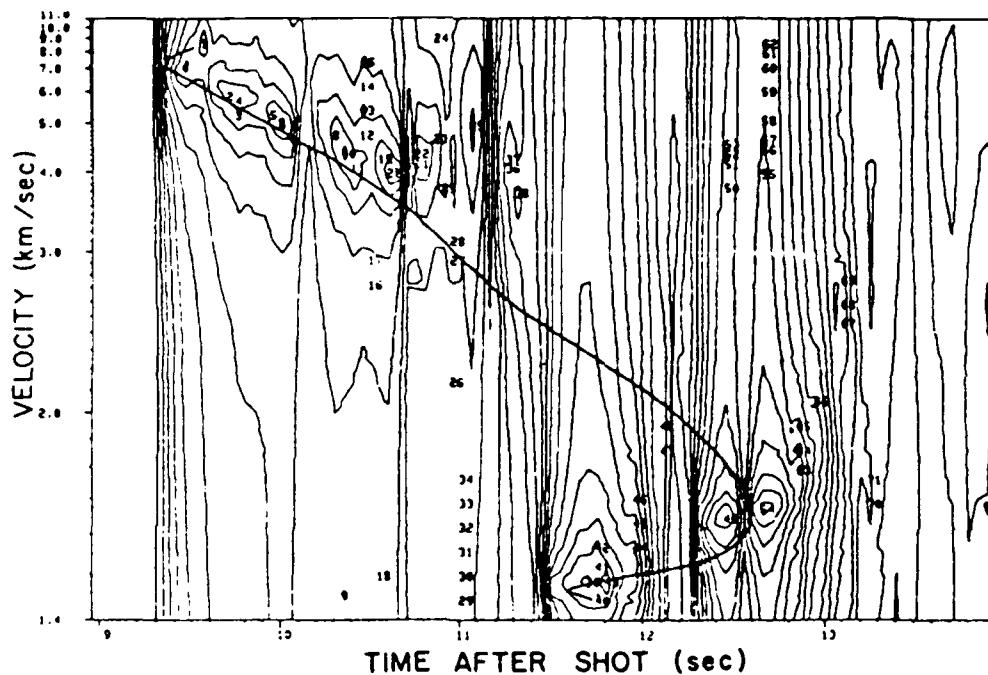


Fig. 10 Example of a slowness-travel (velocity) spectrum from FRAM IV multichannel data. The numbers are local peaks found by a search algorithm. The solid line is the theta function for a WKBJ synthetic program. A good model goes through the large peaks in the spectrum.

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